Procedia Manufacturing
Volume 5, 2016, Pages 536–545
44th Proceedings of the North American Manufacturing Research Institution of SME http://www.sme.org/namrc

Modeling Flank Wear Progression Based on Cutting Force and Energy Prediction in Turning Process

Guicai Zhang[1] and Changsheng Guo[2]

[1]United Technologies Research Center (China), Shanghai, China
[2]United Technologies Research Center, East Hartford, CT, USA
ZhangG@utrc.utc.com, GuoC@utrc.utc.com

Abstract
Flank wear of cutting tools is often used as the tool life criterion because it has high impact on the diametric accuracy of turning. Accurate prediction of tool wear is important for optimizing tool change and other cutting parameters. In this work, a tool wear model is proposed based on the prediction of the cutting force and the energy consumption in turning process. Based on the cutting force prediction using a validated mechanistic force model, the energy consumption in turning can be estimated. A tool flank wear model is developed using the prediction of the cutting energy consumption and considering the impact of the cutting speed. By using the distribution of the cutting force on tool edge and the energy consumption for each revolution of the workpiece, the wear volume distribution on the tool edge for each revolution is predicted. The flank wear (VB) is further calculated using the tool geometry information. The model prediction of flank wear is validated by using tool wear data published in literature. The comparison shows that the model prediction agrees well with the experimental results.

Keywords: Cutting force, Force intensity, Energy consumption, Tool wear, Wear model, Turning process

1 Introduction

Tool wear is a critical problem in metal cutting. It not only increases the production cost but also degrades the product quality. In addition to resulting in poor work surface finish and the work dimension variations, the tool wear also affects the machining dynamics and thus can be monitored by measuring cutting forces and torques and so on (Cheng, 2009). The useful tool life can be defined in terms of the progressive wear. Progressive tool wear mainly includes the wear on the tool rake face (crater wear) and that on the clearance face (flank wear). Flank wear is often used to define the end of effective tool life. As the flank wear land width (*VB*) has grown to a certain level, it will influence the dimensional accuracy and surface finish of the part as well as the stability of the machining process.

It is helpful to be able to predict the tool wear and tool life and as a result to optimize machining process parameters to reduce manufacturing cost and improve product quality. A wear model describes

Selection and peer-review under responsibility of the Scientific Programme Committee of NAMRI/SME

doi:10.1016/j.promfg.2016.08.044

the relation between the machining time and the attained tool wear amount (flank wear VB) for different cutting condition parameters. In the past over thirty years, much work has been contributed to the tool wear modeling. A well-known model for the tool wear rate was developed by Usui et al (Usui & Shirakashi, 1984), and it is based on the idea of contact mechanics and wear. The most famous tool life model is Taylor's model in which the tool life depends mainly on the cutting speed and a constant determined by materials of the tool and the workpiece, feed rate, etc. (Taylor, 1906).

Choudhury et al (Choudhury & Srinivas, 2004) developed a mathematical tool wear model including some important factors like the index of diffusion, wear coefficient, and the hardness of tool, etc. The developed mathematical model was used to relate the wear to the input parameters for a turning operation. Based the prediction results, the authors claimed that the flank wear model is reliable and could be used effectively for tool wear prediction.

Huang et al (Huang & Liang, 2004) studied wear mechanism of Cubic Boron Nitride (CBN) cutters in finish turning of hardened parts and presented a methodology to analytically model the CBN tool flank wear rate as a function of tool/workpiece material properties, cutting parameters. It is shown that adhesion is the main wear mechanism over common cutting conditions.

Yen et al (Yen, Jörg, Lilly, & Atlan, 2004) developed finite element model for tool wear prediction. Based on temperatures and stresses on the tool face predicted by the finite element analysis simulation, tool wear was estimated with acceptable accuracy using an empirical wear model.

Kannan et al. (Kannan, Kishawy, & Surrapa, 2005) presented an energy based analytical model for predicting the tool wear during orthogonal cutting of particulate metal matrix composites (PMMC). The model accounted for the particulate size effect, cutting conditions, material and cutting tool hardness and cutting tool geometry.

Luo et al (Luo, Cheng, Holt, & Liu, 2005) studied the intrinsic relationship between tool flank wear and operational conditions in metal cutting processes using carbide cutting inserts. They proposed a new flank wear rate model combining cutting mechanics simulation and an empirical model. A good agreements between the predicted and measured tool flank wear land width show that the developed tool wear model can accurately predict tool flank wear to some extent.

Marksberry et al (Marksberry & Jawahir, 2008) presented an extended Taylor speed-based dry machining equation to predict tool-wear/tool-life performance in near dry machining (NDM). The validation of the model was performed in an automotive production environment in the machining of steel wheel rims. Tool-wear measurements obtained during the validation of the model showed that NDM can improve tool-wear/tool-life over four times compared to dry machining which underlines the need to develop sustainable models to match current practices.

Attanasioa et al (Attanasioa, Cerettia, & Giardinib, 2013) compared response surface methodology (RSM) and artificial neural networks (ANNs) fitting techniques for tool wear forecasting. Tool life tests on turning of AISI 1045 steel were conducted. Both flank (VB) and crater wears (KT) of the tool were monitored. The comparison shown that ANNs model provides better approximation than RSM in the prediction of the amount of the tool wear parameters.

Mathematical/analytical models are either inaccurate or with difficulties in determining coefficients and they may work well in controlled and well-defined laboratory conditions. The difficulty of these models is the adaptability and validity under industrial conditions. Empirical models rely on lots of experiments and are very time consuming. In this work, a semi-empirical flank wear model based on prediction of cutting force and energy consumption is developed for turning operations. The wear model is based on our previously developed turning force model in which the prediction of the force intensity and energy intensity can be made (Zhang & Guo, 2015). The predicted energy intensity, together with the cutting speed is used to develop the flank wear model. The model is able to predict instantaneous wear volume for each workpiece revolution and the accumulated flank wear VB at a time instance.

2 Cutting Energy Consumption and Tool Flank Wear Model

The flank wear model development starts with the cutting force during the turning operations. A turning model (Zhang & Guo, 2015) is used for predicting the distributions of the cutting force, force intensity and the energy intensity on tool edge. The force intensity distribution on tool edge depicts the force load on unit length of the tool edge length. In actual turning applications, the distribution varies along the tool edge. The energy intensity, which is defined as the cutting energy consumption on unit length of the tool edge, also varies along the tool edge as the actual cutting force and the cutting distance change with the locations on the tool edge. The energy intensity deduced from the cutting force can be related directly to the flank wear volume of the unit length of the tool edge. The tool flank wear model can be represented using the energy intensity including the impact of the cutting speed (or the cutting temperature). Once the wear volume is predicted, the flank wear width VB can be calculated by using the tool geometry information. In the following, the details in the development of the flank wear model will be described.

The predictive force model used in this work includes force equations in three directions: tangential, feed and radial (Zhang & Guo, 2015). Only the tangential force equation is shown here (Equation 1).

$$F_{tc} = \frac{\tau_s}{\sin\phi_n} \cdot \frac{\cos(\beta_n - \alpha_n) + \tan\lambda_s \cdot \tan\eta \cdot \sin\beta_n}{\sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta \cdot \sin^2\beta_n}} \cdot b \cdot h + K_{te} \cdot b \tag{1}$$

where F_{tc} is the cutting force of the turning process, τ_s is the yield shear stress of work material, α_n is the normal rake angle, β_n is the normal friction angle, ϕ_n is the normal shear angle, λ_s is the inclination angle, η is the chip flow angle, K_{te} is the edge force coefficient in tangential direction, b is the width of cut (working edge length), and h is the uncut chip thickness. The yield shear stress τ_s, the edge force coefficient K_{te} and the friction angle β_a ($\beta_n = \tan^{-1}(\tan\beta_a \cdot \tan\lambda_s)$) are determined by experiments.

The accumulative effect of the cutting force on the tool edge can be described by cutting energy. The cutting energy is defined as the cutting force multiplied by the travelling distance of the tool edge:

$$E = F_{tc} \cdot s \tag{2}$$

where F_{tc} is the cutting force of the turning process, s is the travelling distance of the tool edge, and E is the cutting energy.

The energy intensity is defined as the energy consumption on the unit length of the tool edge:

$$E_{in} = E/L_e = F_{tc} \cdot s/L_e \tag{3}$$

where E_{in} is the cutting energy intensity, L_e is the length of the tool edge.

In order to obtain the accurate prediction of the cutting force distribution and the energy intensity distribution, the tool edge is discretized in the force/energy model. For a discretized element of the tool edge i and for one revolution of the workpiece, the energy intensity is defined as:

$$E_{in}(i) = F_{tc}(i) \cdot s(i)/L_e(i) = [K_{tc}(i) \cdot A_c(i) \cdot V_c(i) \cdot t]/L_e(i) \tag{4}$$

where $E_{in}(i)$, $F_{tc}(i)$ $s(i)$, $L_e(i)$, $K_{tc}(i)$, $A_c(i)$, $V_c(i)$ are the energy intensity, cutting force, travelling distance, discretization length of the tool edge, cutting coefficient, cutting area and the cutting speed corresponding to the discretized tool edge element i for one revolution of the workpiece respectively; and t is the time spending for the workpiece rotating one revolution.

At a certain time instance of the turning, the wear volume of the tool edge is directly related to the accumulated energy intensity. The cutting temperature accelerates the tool wear. The major factors influencing the cutting temperature includes material properties of the workpiece, the chip load and the cutting speed. The chip load parameters are included in the equation of the energy intensity. Therefore, the tool flank wear model can be represented as follows:

$$FW_v(i) = C \cdot E_{accum}(i)^p \cdot V_c(i)^q \tag{5}$$

where $FW_v(i)$, $E_{accum}(i)$, and $V_c(i)$ are the flank wear volume, accumulated energy intensity and the cutting speed corresponding to the discretized tool edge element i respectively; and C, p, q are coefficients.

For a turning tool with normal rake angle α_n and normal clearance angle γ_n (Figure 1), the wear volume can be calculated as:

$$FW_v(i) = l \cdot \frac{1}{2} \cdot \overline{BC}^2 \cdot \tan\gamma_n / (1 - \tan\alpha_n \tan\gamma_n) \tag{6}$$

where $\overline{BC} = VB$ is the flank wear width, and l is the length of one discretized tool edge element. Then, we get the flank wear model as the following equation:

$$VB = \sqrt{2C \cdot (1 - \tan\gamma_n \cdot \tan\alpha_n)/(l \cdot \tan\gamma_n) \cdot E_{accum}{}^p \cdot V_c{}^q} \tag{7}$$

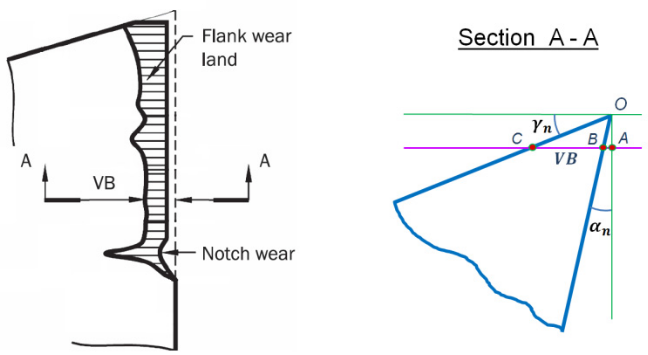
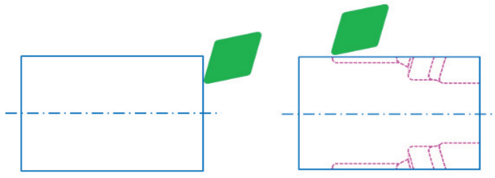


Figure 1: Depict of the tool flank wear (VB)

3 Turning Simulation and Flank Wear (VB) Prediction

In this section, a comprehensive turning example including straight turning, contour turning, taper turning and facing operations are used to demonstrate the model prediction capability. The example includes seven turning steps: 1) straight turning; 2) contour turning; 3) straight turning; 4) facing; 5) taper turning; 6) straight turning; 7) facing. A diamond tool inset with a corner radius of 1.524 mm (0.06 inch) is used. The tool tip angle is 60° and the nominal approach angle is $-15°$. The workpiece material is AISI-1045 steel with shearing stress of 693.4 MPa and the friction angle is 31.6° (Altintas, 2012). The tool insert and the workpiece before and after the seven turning steps are shown in Figure 2. The engagement profiles between the tool and the workpiece for all the seven steps are shown in Figure 3.

A mechanistic force model (Zhang & Guo, 2015) is used to predict the force intensity distribution and the energy intensity distribution on the tool edge. The accumulated energy intensity distribution is further calculated. Then the flank wear volume and VB can be predicted by using the model described in Equation 6.



(a) Before (b) After

Figure 2: Orientation between the tool and the workpiece before and after turning

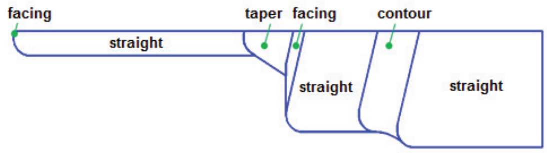


Figure 3: Tool-workpiece engagement profiles for all the seven steps

In the straight turning, taper turning and the facing, the tool motion is linear. In the contour turning the direction of the tool motion is changing. Step 1 (straight turning) and Step 2 (contour turning) are selected as the representative turning operations to analyze the cutting force and force intensity. Figure 4 shows the distributions of the tangential cutting force for all the revolutions in Step 1 (sixty revolutions in total). From the first revolution to the tenth revolution, the working length of the tool increase with the tool feed and the force distributions are changing. From the eleventh revolution (Rev 11-59), the force distributions become coincident. For the last revolution (Rev 60), the force becomes smaller than that of the other revolutions as the feed of the last revolution is smaller than the nominal feed rate due to the constraint of the tool end positon. As the discretized cutting force distributions depend on the interval of the discretization, it is necessary to normalize it with discretized edge length to obtain the comparable force intensity. The force intensity reflects the load on unit edge length of the cutting tool. Figure 5 shows the distributions of the tangential force intensity. The force intensity decreases in the edge portion close to the tool tip due to that the effective thickness become smaller.

Figure 6 and Figure 7 show the distributions of the tangential cutting force and the force intensity for Step 2. Only the selected revolutions are shown for simplicity (seventeen revolutions in total in Step 2 and only six of them are shown). As the direction of the tool feed is changing, the effective tool angles are also changing. So the tangential force and the force intensity are changing from revolution to revolution.

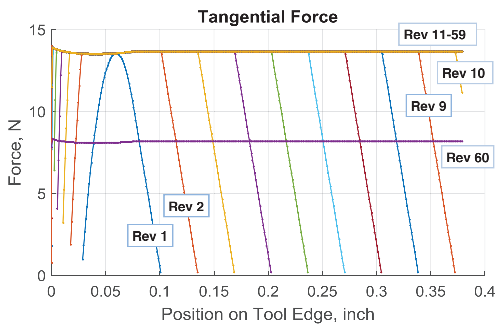


Figure 4: The distribution of tangential cutting force (Step 1)

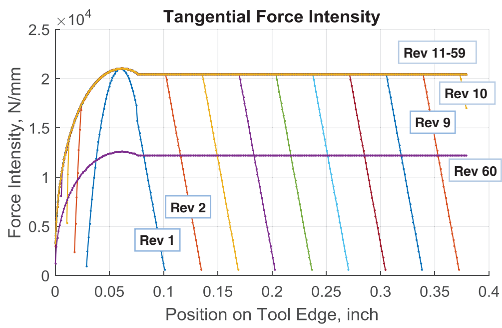


Figure 5: The distribution of the tangential force intensity (Step 1)

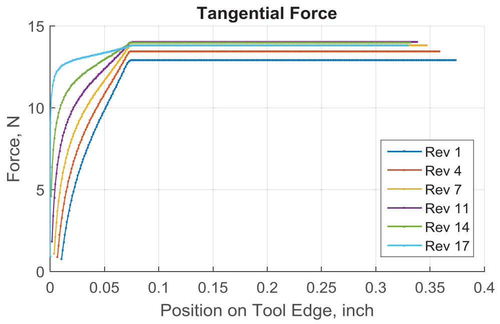


Figure 6: The distributions of the tangential cutting force (Step 2)

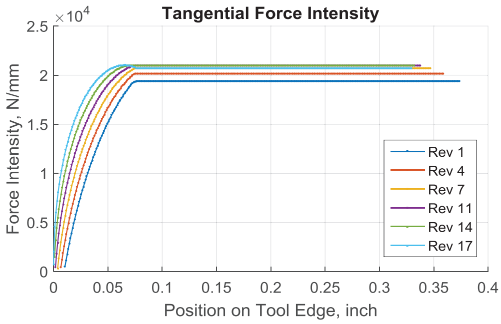


Figure 7: The distributions of the tangential force intensity (Step 2)

Figure 8 (a)-(f) show the distributions of the energy intensity for Step 1-6 respectively. Step 1, 3, 6 are straight turning operations. Step 2 is contour turning operation and the effective chip thickness is smaller as the feed direction is not parallel to the axial direction, so both the force intensity and the energy intensity are smaller than that of the straight turning (Figure 8 (b)). Step 5 is taper turning and the trend of the energy intensity is similar with that of the contour turning (Figure 8 (e)). Step 4 is facing and the effective thickness is significantly smaller than that of the straight turning, so the energy intensity is much smaller (Figure 8 (d)).

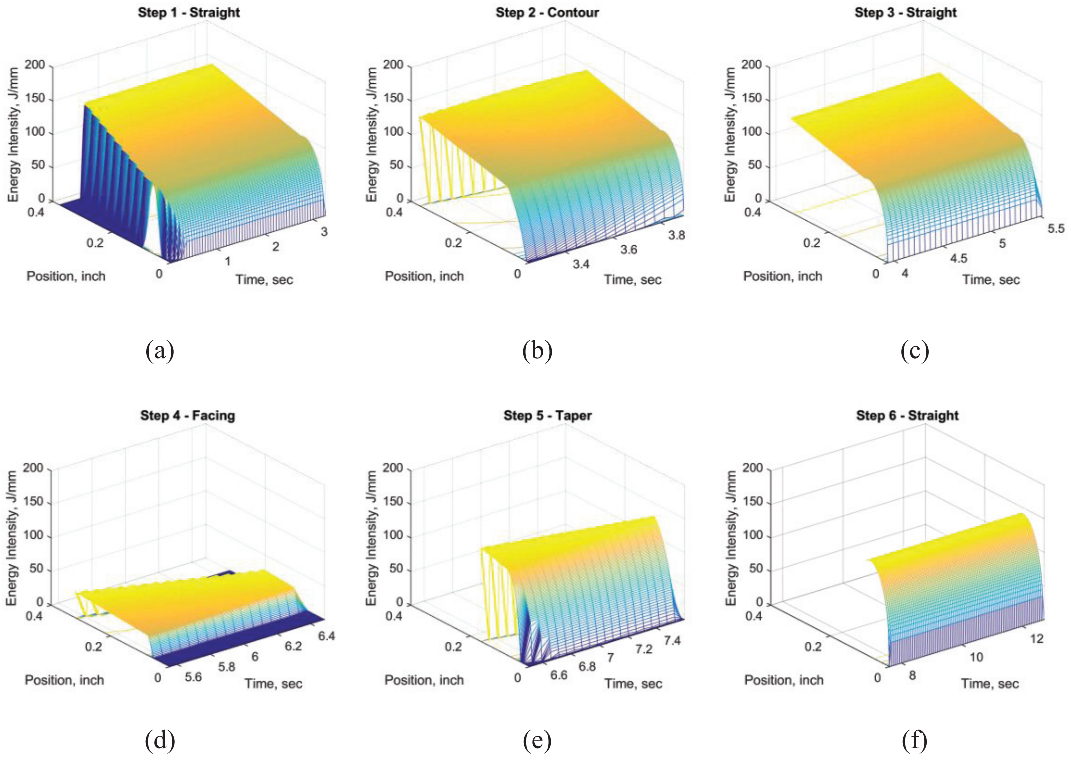


Figure 8: The distribution of energy intensity for Step 1-6

Figure 9 (a)-(f) show the progression of the flank wear from Step 1 to Step 6, that is the wear evolution status revolution by revolution and step by step. Figure 10 (a)-(f) show the wear amount for each revolution and the accumulated effect for all the six steps. It is clearly seen that the worn portion of the tool edge are different for steps due to that the working part of the tool edge is changing for different steps. For example, in Step 4 the facing operation the working and worn part of the tool edge lies in between 0.05 and 0.32 inch (in radial or vertical direction) (Figure 10 (d)). In Step 5 the taper turning the working and worn part of the tool edge lies in between 0 and 0.15 inch (Figure 10 (e)). And, in Step 6 the working and worn part is mainly on the tool corner (between 0 and 0.08), as the depth of cut is small (Figure 10 (f)).

Figure 11 shows the accumulated tool flank wear (VB) at the end of Step 6 and the corresponding tool edge. It is seen that after the six steps turning, the maximum worn location on the tool edge is at about 0.07 inch.

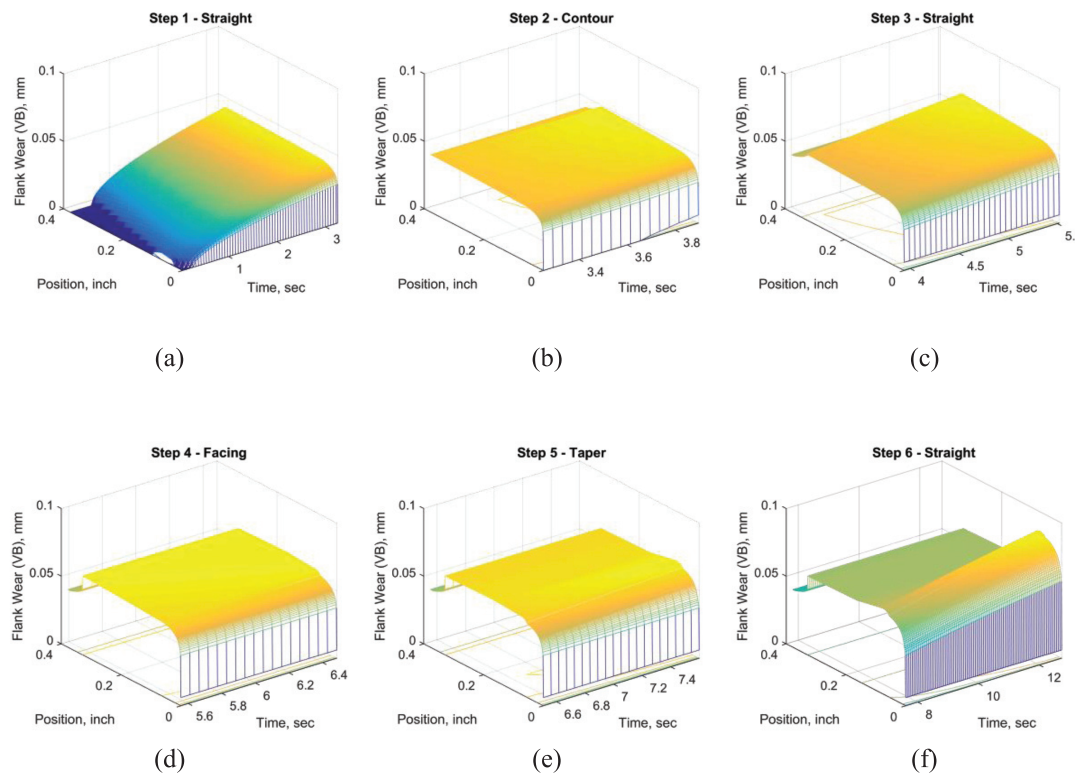


Figure 9: The progression of the tool flank wears (VB)

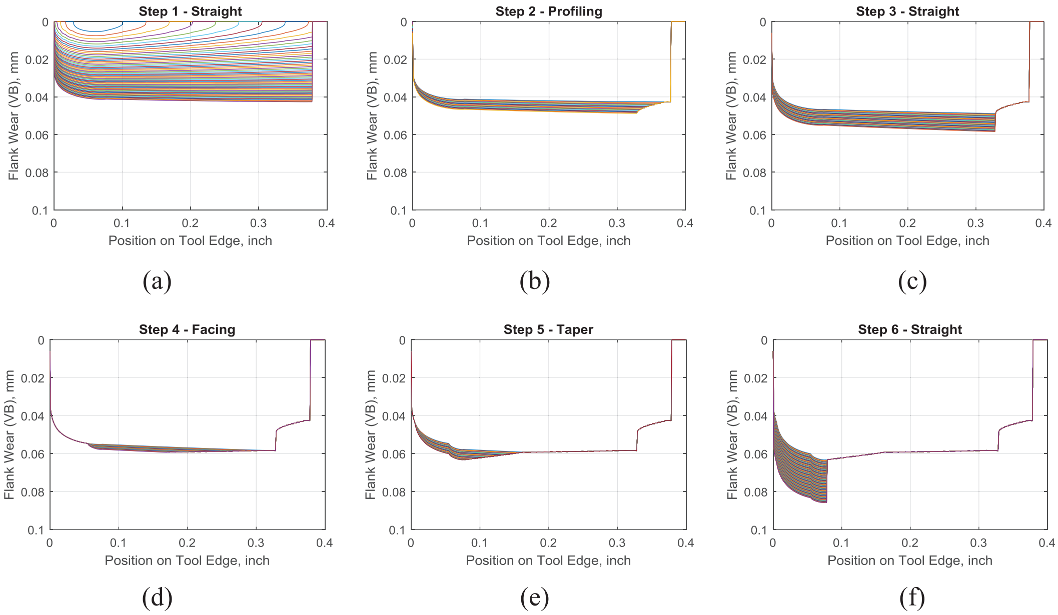


Figure 10: Flank wear (VB) for each revolution and each step and the accumulated effect

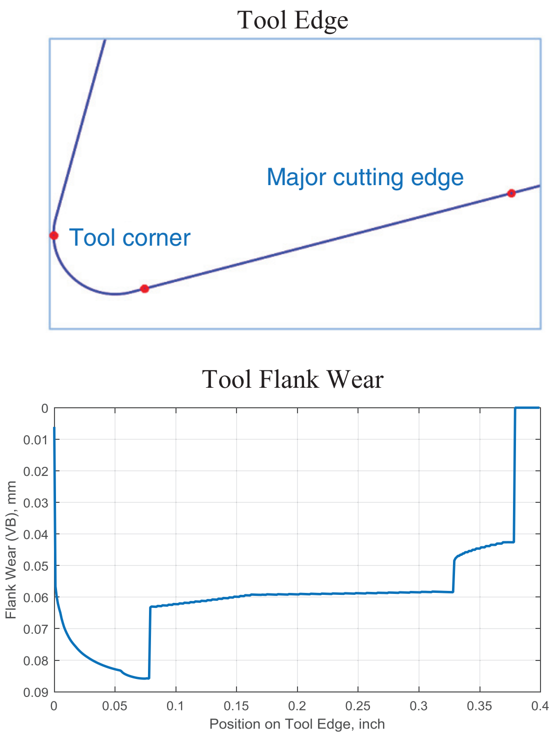


Figure 11: Accumulated tool flank wear (VB) at the end of Step 6

4 Model Validation Against Experimental Data

In this section, experimental tool wear data in literature is used for turning simulation, wear coefficients fitting and model validation. In the experiments, an alloy steel was been machined using turning operation with the carbide insert to evaluate the tool life. The cutting conditions used in the tests are: 2.54 mm depth of cut and 0.18 mm/rev feed rate (Stephenson & Agapiou, 2006). Several inserts were evaluated at four cutting speeds: 90, 120, 150, 180 m/min. The evolution of the tool wear in the tests is shown in Figure 12.

Turning simulations were carried out using the same cutting conditions as used in literature (Stephenson & Agapiou, 2006). More specifically, a cylindrical stock is used for multi-pass straight turning simulation using turning parameters as follows: feed rate of 0.18 mm/rev, depth of cut of 2.54 mm, and cutting speeds of 90, 120, 150, 180 m/min, respectively. The distributions of cutting force intensity and cutting energy intensity were predicted by using the cutting force model (Equation 0) and the cutting energy intensity model (Equation 4). Using the prediction of the accumulated energy intensity and the corresponding cutting speed and the measured wear VB values in the literature, the wear coefficients in Equation 7 are fitted as: $\mathrm{C} = 3.106e - 11, p = 0.734, q = 2.204$, the R-squared value of the linear regression is 0.954. The predictions of flank wear VBs can be obtained by using these fitted coefficients in the tool wear model.

Table 1 shows the comparison between the model predicted flank wear VB and the measured VB values in the tests. It is shown that the predicted flank wear VBs match the experimental values well.

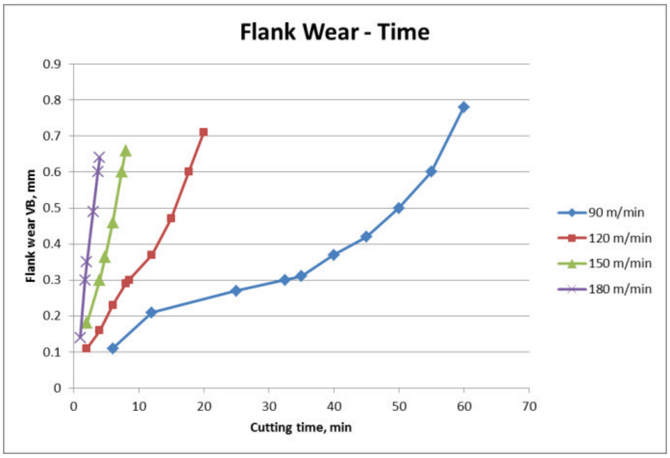


Figure 12: Experimental data of tool wear (Stephenson & Agapiou, 2006)

Cutting speed (m/min)	Feed rate (mm)	Depth of cut (mm)	Cutting time (min)	Measured VB (mm)	Predicted VB (mm)	Error (%)
90	0.18	2.54	25	0.27	0.2879	6.61
120	0.18	2.54	8	0.29	0.2904	0.15
150	0.18	2.54	4	0.30	0.3363	12.09
180	0.18	2.54	2	0.35	0.3454	1.31

Table 1: Comparison between the predicted VB and the measured VB in the test

5 Conclusions

In this work, a cutting energy based tool wear model is proposed. Based on the prediction of the cutting force, the cutting energy consumption in the turning is estimated. Then a tool flank wear model is developed by using the cutting energy consumption and the cutting speed. In the model, the wear volume is the exponential function of the energy intensity and the cutting speed. The flank wear (VB) is further calculated by using the predicted wear volume and the tool geometry information. The coefficients are obtained by using tool wear experiments. The model prediction of flank wear is validated by using experimental data on tool wear from literature. The comparison between the prediction and the experimental measurements show that the both are well matched.

References

Altintas Y. *Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design, 2nd ed.* New York: Cambridge University Press, 2012.

Attanasioa A, Cerettia E and Giardinib C. Analytical Models for Tool Wear Prediction during AISI 1045 Turning Operations. *Procedia CIRP* 2013; 8:218-223.

Cheng K. *Machining Dynamics - Fundamentals, Applications and Practices.* London: Springer-Verlag London Limited, 2009.

Choudhury SK and Srinivas P. Tool wear prediction in turning. *Journal of Materials Processing Technology* 2004; 153-154:276-280.

Huang Y and Liang SY. Modeling of CBN Tool Flank Wear Progression in Finish Hard Turning. *Journal of Manu. Sci. And Engineering* 2004; 126(1): 98-106.

Kannan S, Kishawy H and Surrapa M. (2005). Modeling of tool flank wear progression during Orthogonal machining of metal matrix composites. *Transactions of the North American Manufacturing Research Conference* 2005; pp.605-612.

Luo X, Cheng K, Holt R and Liu X. Modeling flank wear of carbide tool insert in metal cutting. *Wear* 2005; 259(7-12):1235-1240.

Marksberry PW and Jawahir IS. A comprehensive tool-wear/tool-life performance model in the evaluation of NDM (near dry machining) for sustainable manufacturing. *Journal of Machine Tools & Manufacture*, 2008; 48(7-8):878-886.

Stephenson DA and Agapiou JS. *Metal Cutting Theory and Practice, 2nd Edition.* CRC Press, Taylor & Francis Group, 2006.

Taylor FW. *On the Art of Cutting Metals.* American Society of Mechanical Engineers, 1906.

Usui E and Shirakashi T. Analytical Prediction of Cutting Tool Wear. *Wear* 1984; 100(1): 129-151.

Yen Y-C, Jörg S, Lilly B and Atlan T. Estimation of tool wear in orthogonal cutting using the finite element analysis. *Journal of Materials Processing Technology* 2004; 146(1): 82-91.

Zhang G and Guo C. Modeling of Cutting Force Distribution on Tool Edge in Turning Process. *Procedia Manufacturing* 2015; 1:25-27.